GMRT Observer's Manual

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1 An Overview of the GMRT

The Giant Metrewave Radio Telescope (GMRT) is located near Khodad village, which is about 80 km north of Pune. The GMRT consists of an array of 30 antennae, each of 45 m diameter, spread over a region of 25 km diameter. Amongst the multi-element earth rotation aperture synthesis telescopes operating at meter wavelengths, the GMRT has the largest collecting area. The interferometer has a hybrid configuration with 14 of its 30 antennas located in a central compact array with size $\sim$1.1 km and the remaining antennas distributed in a roughly 'Y' shaped configuration, giving a maximum baseline length of $\sim$25 km. The baselines obtained from antennas in the central square are similar in length to the VLA D-array configuration, while the baselines between the arm antennas are comparable in length to the baseline lengths between VLA A-array and VLA B-array configurations. Hence, a single observation with the GMRT samples the (u, v) plane adequately on both short and long baselines with reasonable sensitivities. The GMRT can also be configured in array mode, where it acts as a single dish by adding the signals from individual dishes. This mode of operation is used for studying compact objects like pulsars, which are effectively point sources even for the largest interferometric baselines. The maximum instantaneous operating bandwidth at any frequency band is 33 MHz. Each antenna provides signals in two orthogonal polarisations, which are processed through a heterodyne receiver chain and brought to the central receiver building, where they are converted to baseband signals and fed to the digital back-end consisting of correlator and pulsar receiver.

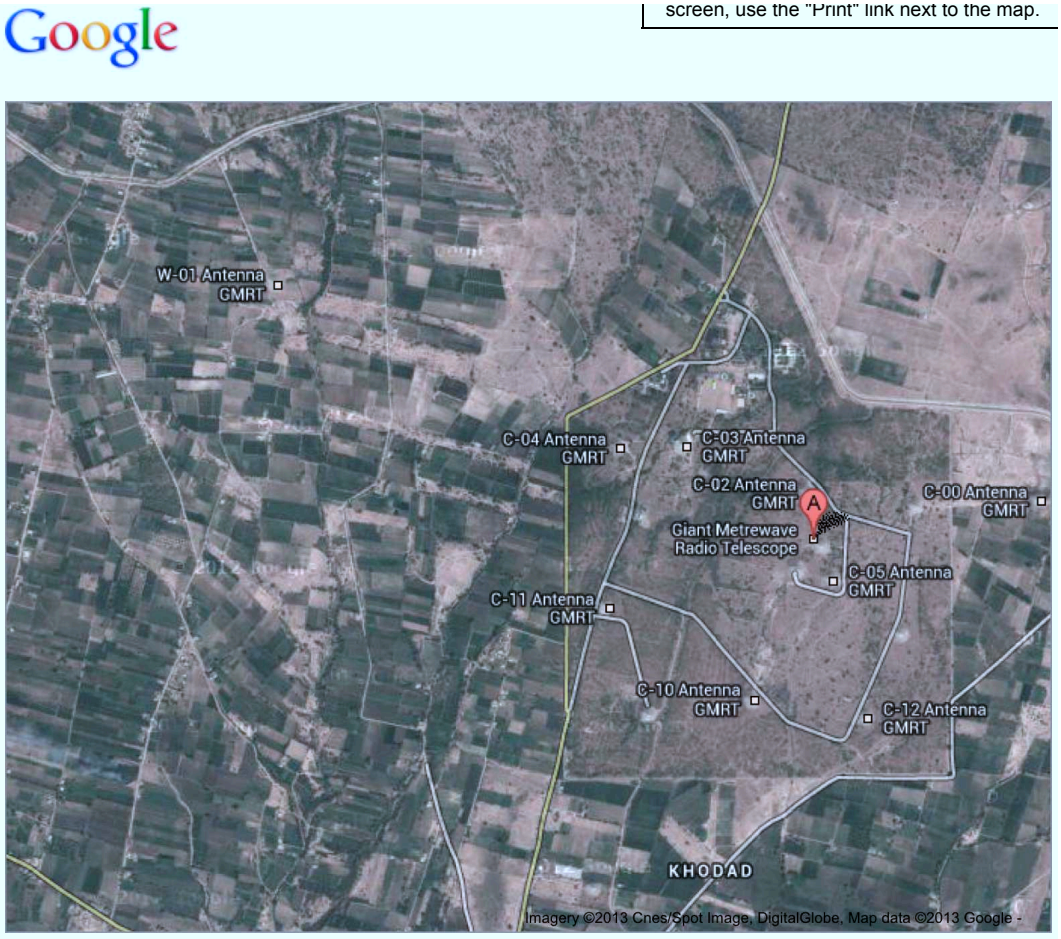

Figure 1: Location of the GMRT array as seen on the Google-maps (latitude and longitude are provided in Section 2.1 below).

2 Specifications of the GMRT

2.1 Antennas

The GMRT antennas are alt-azimuth mounted parabolic prime-focus dishes. While the dishes can go down to an elevation of 16°, at present, the elevation limit has been set at 17°, giving a declination coverage from -53° to $+90^\circ$. The slew speed of the antennas is 20° min^{-1} on elevation axis and 30° min^{-1} on azimuth axis, and they are not operated when winds are higher than 40 km h^{-1}. The reference antenna, C02 of the array is located at

latitude = 19.1°N,
longitude = 74.05°E,
altitude = 588 m.

2.1.1 Observing Frequency Bands

There is a rotating turret at the focus on which the different feeds are mounted. The feeds presently available are the 150, 325, 610/235 and the $1000-1450$ MHz feeds. The $1000-1450$ MHz feed, L-band feed is subdivided into 1060, 1170, 1280 and 1390 MHz sub-bands. The reflecting surface is formed by wire mesh and the efficiency of the antennas varies from 60% to 40%, from the lowest to the highest frequency. Both the orthogonal polarisations are brought to the control room from each antenna. The polarisations are circular for all feeds except the 1420 MHz feeds, which are linear. The 610 MHz and 235 MHz feeds are coaxial, allowing simultaneous dual frequency observations to be carried out at these two frequency bands, albeit for only one polarisation per band.

2.1.2 Bandwidth

The new GMRT Software Backend (GSB) supports a maximum bandwidth of 32 MHz. Users should consult the observatory regarding usable RF bandwidth at the lower frequencies because of RFI. For 150 MHz and 235 MHz, the recommended IF bandwidth is 6 MHz; however, 16 MHz is also usable, albeit with some caution.

2.1.3 Resolution

The approximate synthesized beam size (full width at half-maximum) for a full synthesis observation at each of the observing bands is given below:

150 MHz: $\sim 20''$
235 MHz: $\sim 13''$
325 MHz: $\sim 9''$
610 MHz: $\sim 5''$
1280 MHz: $\sim 2''$

2.1.4 Field of View

The field of view, diffraction-limited response of the individual antennas is

$$\theta \simeq 85.2 \times \frac{325 \text{ GHz}}{\nu},$$

where θ, the half-power beam-width is in arcmin and ν is the frequency. These are

150 MHz: $186' \pm 6'$

235 MHz: $114' \pm 5'$

325 MHz: $81' \pm 4'$

610 MHz: $43' \pm 3'$

1280 MHz: $26.2' \pm 2'$

2.1.5 Primary Beam

The coefficients of an eighth order polynomial fit to the antenna primary beam

$$1 + (\frac{a}{10^3})x^2 + (\frac{b}{10^7})x^4 + (\frac{c}{10^{10}})x^6 + (\frac{d}{10^{13}})x^8,$$

where a, b, c and d are PBPARM(3), PBPARM(4), PBPARM(5) and PBPARM(6), respectively. These can be directly plugged into `AIPS` task `PBCOR` are

150 MHz: PBPARM(1) = 0.1; PBPARM(2) = 1; PBPARM(3) = -4.04;
PBPARM(4) = 76.2; PBPARM(5) = -68.8; PBPARM(6) = 22.03; PBPARM(7) = 0

235 MHz: PBPARM(1) = 0.1; PBPARM(2) = 1; PBPARM(3) = -3.366;
PBPARM(4) = 46.159; PBPARM(5) = -29.963; PBPARM(6) = 7.529; PBPARM(7) = 0

325 MHz: PBPARM(1) = 0.1; PBPARM(2) = 1; PBPARM(3) = -3.397;
PBPARM(4) = 47.192; PBPARM(5) = -30.931; PBPARM(6) = 7.803; PBPARM(7) = 0

610 MHz: PBPARM(1) = 0.1; PBPARM(2) = 1; PBPARM(3) = -3.486;
PBPARM(4) = 47.749; PBPARM(5) = -35.203; PBPARM(6) = 10.399; PBPARM(7) = 0

1280 MHz: PBPARM(1) = 0.1; PBPARM(2) = 1; PBPARM(3) = -2.27961;
PBPARM(4) = 21.4611; PBPARM(5) = -9.7929; PBPARM(6) = 1.80153; PBPARM(7) = 0

More details such as the fitted polynomial, methodology, etc. are available at
`http://www.ncra.tifr.res.in:8081/~ngk/primarybeam/beam.html` .

2.1.6 Sensitivity

The system temperature is

150 MHz: 615 K†

235 MHz: 237 K†

325 MHz: 106 K

610 MHz: 102 K

1280 MHz: 73 K

† The system temperature measurements are with Solar attenuator switched on,
and the antenna gain is

150 MHz: 0.33 K Jy^{-1} Antenna^{-1}

235 MHz: 0.33 K Jy^{-1} Antenna^{-1}

325 MHz: 0.32 K Jy^{-1} Antenna^{-1}

610 MHz: 0.32 K Jy^{-1} Antenna^{-1}

1280 MHz: 0.22 K Jy^{-1} Antenna^{-1}

The RMS noise sensitivity equation is,

$$\Delta S \;=\; \frac{\sqrt{2}\,k\,T_{\rm sys}}{\eta_a\,\eta_c\,A\,\sqrt{(n_b)\,n_{\rm IF}\,\Delta\nu\,\tau}},$$

and the on-source integration time τ is computed *via*,

$$\tau = (\frac{\sqrt{2}\, k\, T_{\rm sys}}{\Delta S \times \eta_a\, \eta_c\, A})^2 \times \frac{1}{(n_b)\, n_{\rm IF}\, \Delta\nu}$$

where ΔS is the required RMS noise (Jy), $T_{\rm sys}$ is the system temperature (K), and $[(\eta_a\ A)/(2k)]\ =\ G$ is the antenna gain (K/Jy), where η_a (see Section 2.1.1) and η_c ($\simeq 1$) being aperture and correlator efficiencies respectively. A is the geometrical area of the antenna, n_b is the number of baselines, $n_{\rm IF}$ is the number of IF channels, and $\Delta\nu$ (Hz) is the bandwidth of each sideband (or channel width for spectral line observations). $n_{\rm IF}$ = $n_{\rm pol}$ + $n_{\rm SB}$, where $n_{\rm pol}$ is the number of polarisations (2 for the GMRT) and $n_{\rm SB}$ is the number of sidebands.

2.2 System Parameters

Below in the Table 1, we list the system parameters. It also lists best RMS sensitivities and typical dynamic ranges achieve in a mapped field, which are known to us.

	Frequency (MHz)				
	151	235	325	610	1420
Primary beam (HPBW, arcmin)	186 $\pm$6	114 $\pm$5	81 $\pm$4	43 $\pm$3	(24 $\pm$2)$\times$(1400/f)
System temperature ($\rm T_{system}$, K)					
Receiver temperature ($\rm T_R$)	295†	106†	53	60	45
Typical $\rm T_{sky}$ (off Galactic plane)	308	99	40	10	4
Typical $\rm T_{ground}$	12	32	13	32	24
$\rm T_{system}$ (= $\rm T_R + T_{sky} + T_{ground}$)	615	237	106	102	73
Antenna gain (K Jy^{-1} Antenna^{-1})	0.33	0.33	0.32	0.32	0.22
Synthesized beam (FWHM)					
– Full array (arcsec)	20	13	9	5	2
– Central square (arcsec)	420	270	200	100	40
Largest detectable structure (arcmin)	68	44	32	17	7
Usable frequency range					
– observatory default (MHz)	150–156	236–244	305–345	580–640	1000–1450
– allowed by electronics (MHz)	130–190	230–250	305–360	570–650	1000–1450
Fudge factor (actual to estimated time)					
– for short observations	10	5	2	2	2
– for long observations$^\#$	5	2	2	1	1
Best RMS sensitivities achieved (mJy)‡	0.7	0.25	0.04	0.02	0.03
Typical dynamic range achieved	$>$1500	$>$1500	$>$1500	$>$2000	$>$2000

† With default solar attenuator (14 dB).
# For spectral observations fudge factor is close to 1.
‡ So far known to us!

Table 1: Measured system parameters of the GMRT

2.3 Data Rates

For the correlator configurations discussed in Section 2.7, integration time Δt, and recording both self and cross correlation coefficients, the data rate is

$$= 1.86 \times [\frac{N_{\rm ant} \times (N_{\rm ant}+1)}{(30 \times 31)} \times (\frac{2 \text{ sec}}{\Delta t})] \text{ MB sec}^{-1},$$

$$= 3.35 \times [\frac{N_{\rm ant} \times (N_{\rm ant}+1)}{(30 \times 31)} \times (\frac{2 \text{ sec}}{\Delta t})] \text{ GB hr}^{-1},$$

which corresponds to $\sim$0.1 TB day^{-1} when using the full 30-element array with 2 sec integrations, 2 (RR and LL) total intensity polarisations and 512 spectral channels.

2.4 Subarrays

GMRT supports multiple subarrays for users, where the array is divided into smaller groups of antennas. It can be configured in array mode, where it acts as a single dish by adding the signals from individual dishes. Note that up to a maximum of five subarrays are possible at any given time and it is not possible to have different correlator settings for these subarrays. This mode of operation is used for studying compact objects like pulsars, which are effectively point sources even for the largest interferometric baselines.

2.5 Pointing Accuracy and Pointing Correction

The typical pointing accuracy of a GMRT antenna is 1 arcsec and the typical tracking accuracy is 10 arcmin. A pointing model has been in use since observing cycle-15, which can be applied online during the observations; it updates the antenna pointing offsets every half an hour or so during an observing run, using commands included in the user's `observe file`. Elevation dependent offsets are seen in a few antennas, which can again be corrected using a pointing model. If a user does not want to apply the dynamic pointing model, the control room should be informed before the start of the observing run.

2.6 Polarisation

Polarisation observations are now possible using GMRT and several users have carried out full polar observations at 610 MHz. Interested users could look at the following article

`http://arxiv.org/abs/1309.4646` .

Despite the on-axis instrumental polarisation at GMRT being of large amplitude and highly frequency-dependent, this article demonstrates the viability of the GMRT for full-polarisation, wide-field spectropolarimetry.

2.7 GSB Configurations

The current GMRT Software Back-end (GSB) offers relatively more options as compared to its earlier hardware counterpart. Current status and latest news about the GSB can be found at

`http://gmrt.ncra.tifr.res.in/gmrt_hpage/sub_system/gmrt_gsb` .

Table 2 presents the available modes of the back-end. Briefly, from cycle-20 onwards the GSB is the back-end at the observatory, the older hardware back-ends have been decommissioned, and the details of available modes are as follows:

The new GSB back-end supports a maximum bandwidth of 32 MHz. However, users should consult the observatory regarding usable RF bandwidth at the lower frequencies because of RFI. For 150 MHz and 235 MHz, the recommended IF bandwidth is 6 MHz; however, 16 MHz is also usable, albeit with some

caution. Currently, the interferometre polarisation observations are supported on an experimental basis and the analysis requires a lot of hard work. Walsh and Noise Cal modulation for real time T_{sys} measurements are currently not supported and hence, absolute flux calibration in regions where the system temperature varies (like the galactic plane) is not automatic. Normal integration times used are 8 or 16 s but more rapid sampling (down to 2 s) can be done, subject to the availability of enough disk space for recording the larger data volume. Users requiring such modes should consult the 'Operations" group at the observatory.

2.7.1 Correlator

It presently supports the following modes of interferometric observations:

i Full bandwidth, non-polar and full polar interferometric observations in the "16 MHz" and "32 MHz" modes, with a choice of 256 or 512 spectral channels across the full band, and with integration time of 2 sec or larger.

ii Spectral zoom modes (for spectral line observations) where the input band is filtered and decimated by factors 4, 8, 16, 32, 64, 128 while keeping the number of spectral channels across the reduced bandwidth fixed at 256 or 512 – this mode will only work within the "16 MHz" mode.

iii Variable spectral resolution, with a choice of 64, 128, 256, 512 or 1024 (note: 1024 channel mode has not been tested and debugged thoroughly) spectral channels across the band of observation. Reduced spectral channels will allow for correspondingly faster dump times for the visibility data.

2.7.2 Beamformer

The beamformer is especially used for pulsar observations and it presently supports the following modes of array beamformer:

i Incoherent array (IA) and phased array (PA) beam modes with total intensity output; here at present the fastest sampling time is 60 μsec.

ii PA beam mode with full polar output at correspondingly reduced time resolutions (see Table 2).

iii Full time resolution voltage beam data with facility for offline coherent dedispersion of the same.

iv Multi-subarray beam modes (IA or PA) with full bandwidth, for up to two subarrays, with independent GMRT Array Combiner (GAC) antenna selection control for each subarray.

Additional, a special feature of the GSB being, raw voltage dump data, i.e.,

v raw voltage recording of the digitized voltage signals from each antenna (4 bit samples) for "16 MHz" mode, followed by limited capability for offline playback and correlation / beamformer – the frequency of usage of this mode of operation will be restricted by the total volume of disk space available for recording, as well as the time taken for the offline analysis. The observatory offers very limited capabilities for long-term back-up of the raw voltage dump data and the user will be responsible for clearing the large volumes of data from the disks within a stipulated time, typically a week or less. Users desirous of using this mode should check with the observatory well in advance.

2.8 Snapshots

The two-dimensional geometry along with a hybrid configuration with 14 of its 30 antennas located in a central compact array with size $\sim$1.1 km and the remaining antennas distributed in a roughly 'Y' shaped configuration, giving a maximum baseline length of $\sim$25 km of the GMRT allows a snapshot mode whereby short, "snapshot" observations can be made to map detailed source structure with good angular resolution and with reasonably good sensitivity.

Before considering snapshot observations using GMRT, users should first determine if the goals desired can be achieved with the existing TIFR GMRT Sky Survey (TGSS),

http://tgss.ncra.tifr.res.in/ ,

which is an all sky survey at 150 MHz.

Available modes of the GSB

(Release Ver. 2.3 18 January 2012)

	Observation Type		Usage Mode	Input IF BW (MHz)	Acquisition BW or Final o/p BW (MHz)	Number of Channels	Output Time Resolution
1	Interferometry : Continuum		Total Intensity (32 MHz mode)	32,16,6	32	512, 256	2,4,8..(sec)
			Total Intensity (16 MHz mode)	16,6	16	512, 256	2,4,8..(sec)
						128	0.5,1,2..(sec)
						64, 32	0.25,0.5,1..(sec)
			Full Stokes (32 MHz mode)	32,16,6	32	512(*), 256	2,4,8..(sec)
			Full Stokes (16 MHz mode)	16,6	16	512, 256	2,4,8..(sec)
2	Interferometry : Spectral Line		Total Intensity (16 MHz and lower BW modes)	16,6	16 / N (N=4,8,16..128) (viz. 4, 2, 1, 0.5,0.25 & 0.125 MHz)	512, 256	2,4,8..(sec)
3	Array: Beams	IA	Total Intensity (32 MHz mode)	32,16,6	32	512, 256	Pre : (#) Post: 1,2,4
			Total Intensity (16 MHz mode)	16,6	16 / N (N=4,8,16) (viz. 4,2,1 MHz)	512, 256	Pre: (#) Post: 1,2,4
		PA	Total Intensity (32 MHz mode)	32,16,6	32	512, 256	Pre: (#) Post:1,2,4
			Total Intensity (16 MHz mode)	16, 6	16 / N (N=4,8,16) (viz. 4,2,1 MHz)	512, 256	Pre: (#) Post: 1,2,4
			Full Stokes (16 MHz mode)	16,6	16	512, 256	Pre: (#) Post:1,2,4
			Voltage Beam (32 MHz mode)	32,16,6	32	512, 256	15 nsec (@)
			Voltage Beam (16 MHz mode)	16,6	16	512, 256	30 nsec (@)
4	Raw Dump		Raw voltages from all antennas	16,6	16		30 nsec at 4 bits per sample

Notes :

(*) Released on trial basis : set lta-visibility pre-integration to 4sec and beam output 245.76 uSec.

(#) Regarding beam integration and beam-data-host

BW	CHANNEL	PRE-INTEG	IFR	Beam-Stokes	Data-Nodes (Beam1-Beam2)
16.666	256	30.72 uSec	TI	IA(TI):PA(TI)	node33-34
16.666	512	61.44 uSec	TI	IA(TI):PA(TI)	node33-34
16.666	256	61.44 uSec	FS	IA(TI):PA(FS)	node33-34
16.666	512	122.88 uSec	FS	IA(TI):PA(FS)	node33-34
33.333	256	30.72 usec	TI	IA(TI):PA(TI)	node33-34
33.333	512	61.44 usec	TI	IA(TI):PA(TI)	node33-34
33.333	256	61.44 usec	FS	IA(TI):PA(FS)	node47-48 with XNET
33.333	512	245.76 usec	FS	IA(TI):PA(FS)	node47-48 with XNET

(@) Output data is in spectral voltage form; needs one inverse FT to get voltage time series with time resolution of 15 nsec for 32 MHz mode and 30 nsec for 16 MHz mode.

Table 2: Available modes of the GSB for continuum, spectral, pulsar and raw-dump observations. All details, including standard-operating-procedure, etc. are available at GSB-SOP.

2.9 GMRT Calibrators: Amplitude, Bandpass and Phase Calibration

The flux density calibrators, 3C 48 (0137+331, J2000), 3C 147 (0542+498, J2000) and 3C 286 (or 1331+305, J2000) are used for both, amplitude and bandpass calibration. Together these three calibrators almost cover the entire 24 hr observing run. The flux density scale used for for the observing bands at GMRT is based on the Baars et al. (1977 Astron. Astrophys., 61, 99) scale.

A suitable list of phase calibrators selected from the complete VLA calibrator list that are appropriate for GMRT is being collated at 610 and 240 MHz. Once it is ready, it would be made available. Till then, users can consult the VLA calibrator list for appropriate phase calibrator for their observation. Since the mapped field-of-view (Section 2.1.4) are larger at low frequencies, users should map the calibrator field and use these solutions, instead of assuming it to be a field with only one dominant point source at the phase centre.

3 Radio Frequency Interference

Radio-frequency interference (RFI) signals are among the main factors limiting the performance of radio telescopes. RFI constricts the available frequency space, effectively increases system noise and corrupts calibration solutions. The effect is particularly strong at frequencies below 1 GHz. Although, the RFI environment at GMRT is fairly decent, especially at frequencies below 235 MHz band it can be quite alarming. While the strongest source in a field is typically only a few Jy, the RFI can occasionally reach several hundred Jy in some channels in the 150 and 235 MHz bands. However broadband RFI of up to several tens of Jy causes even more damage: currently available tools, including the `AIPS` task `FLGIT` provide some solution.

As mentioned above, the RFI environment can be bad at 150 MHz and is sometimes a problem at 235 MHz; the situation is usually better at night time and on weekends. (For these two bands, it is recommended to use the solar attenuators in the common box, to minimize the possibilities of saturating the downstream electronic chain due to RFI.) Observations at 325 MHz can be hampered sometimes due to RFI from nearby aircraft activity, especially during day time. Due to increasing interference from mobile phone signals around 950 MHz, the all-pass mode at 1400 MHz band is no longer supported as an official mode, and consequently observations below 1000 MHz in this band are not supported. Even for the lowest of the 4 sub-bands of the 1400 MHz band (covering 1060 ± 60 MHz), the user is advised to check for effects of RFI.

Please refer to Sections 2.1.2 and 4.2.1.2 for usable bandwidth and default settings, respectively. Users are also informed that since cycle-21, night time scintillation has been occasionally seen, even at the 1400 MHz band, and the probability of scintillation is higher close to the equinoxes.

4 Observing with the GMRT

4.1 Regular Observing Proposals for TAC

The GMRT Time Allocation Committee (GTAC) invites proposals for two Cycles (April to September and October to March). The deadline for receiving these proposals is 17:00 HRS IST (UTC+5.5 hrs), January 15, and July 15. All proposals are to be submitted online via the NCRA Archive and Proposal Management System (NAPS), available at

`http://naps.ncra.tifr.res.in` ,

which provides a password authenticated, web browser based interface for proposal submission. Note that proposal may be submitted only by the PI. All co-I's also need to be registered users of the system. All proposals are processed by GTAC with external refereeing as needed with inputs from the GMRT Observatory on technical issues and the proposers are sent intimations of the time allocation. The call for proposals, the

status of the GMRT, and a set of guidelines for GMRT users can be found at
http://www.ncra.tifr.res.in/ncra/gmrt/gtac .
Additionally, frequently asked questions on GMRT proposal submission are available at
http://www.ncra.tifr.res.in:8081/~yogesh/proposalfaq.html ,
and the quick-start guide to GMRT proposal submission is available at
http://www.ncra.tifr.res.in:8081/~yogesh/quickstartguide.html .

After a proposal has been allotted time and scheduled, further queries regarding travel logistics (see Section 6.1) can be addressed to the "Secretary - Operations"
(secr-ops AT ncra DOT tifr DOT res DOT in).
Any queries related to the observing schedule should be sent to
gmrtschedule AT ncra DOT tifr DOT res DOT in ,
and regarding other aspects of the observations should be sent to
gmrtoperations AT ncra DOT tifr DOT res DOT in .
In the event of potential overlap of interests of different proposers, GTAC will try and encourage collaboration or sharing of data by bringing the concerned individuals into contact with each other.

Note that starting from 2012, GMRT has entered into an intensive phase of the ongoing upgrade (see Section 6), and this requires additional day time slots for engineering activity. The observatory tries its best to maintain the availability of 26 antennas for all the scientific observations. Some of the existing observation modes and available flexibilities of settings for observations may be partially affected by the changes implemented as part of the upgrade activities. In the regard, the users are advised to read the GMRT status document, available at
http://www.ncra.tifr.res.in/ncra/gmrt/gtac ,
which is updated at every proposal deadline.

4.1.0.1 Proposing for GMRT Observations: Checklist

i 'Register' and 'login' at the
http://naps.ncra.tifr.res.in ,
ii choose 'Create Proposal' and follow necessary steps.
iii Remember to attach a self-contained 'Scientific Justification' not exceeding 3000 words. Preprints or reprints will be ignored, unless reporting previous GMRT observations. A brief status report (not exceeding 150 words) on each previous proposal should be appended to the scientific justification.

Note: when your proposal is scheduled, the contents of the cover sheets become public information. Any supporting pages are for refereeing purpose only.

4.1.1 TAC Approved Proposals

4.1.2 Director's Discretionary Time

In addition to regular GTAC proposals, users can also avail

i Target of Opportunity: Target of Opportunity (TOO) time is primarily intended for short lived, unexpected/ unpredicted phenomena or time dependent astronomical phenomena.
ii Exploratory Proposals: Here, the time is primarily meant for pilot observations or feasibility studies which might lead to future GTAC proposals and confirmatory observations.

Both types of time allocation are subject to availability of time and will be evaluated on the basis of scientific merit by the relevant referees, and are cleared by the Centre Director, NCRA. Requests for allocation of TOO and DDT should also be submitted using the NAPS interface, code "DDT". Such observations will be scheduled in the empty "white" slots
(http://www.ncra.tifr.res.in:8081/~gmrtoperations/gtac/request.html),

without affecting the scheduled GTAC observations, as far as possible. the guidelines followed at the observatory for allocating these "white" slots are available at

http://www.ncra.tifr.res.in/ncra/gmrt/gtac .

4.2 Planning the Observing Run

If you are ready to observe, visit the following site for preparing your observations.

http://www.ncra.tifr.res.in/gmrt_hpage/Users/Help/help.html .

Also check that the following tasks (see Section 4.2.1.1 and 4.2.2.1) have been accomplished:

4.2.1 Continuum / Spectral-line

From cycle-20 onwards, the GSB is the only back-end available at the GMRT. The older, hardware back-ends have been decommissioned. All 30 antennas are in use and feeds for all frequencies are available. At a given time, the observatory will try to make at least 26 antennas available for any observation. Programs that critically depend on the short spacing antennas (C05, C06 and C09, with $\sim$ 100 m separation) must indicate this in the GTAC proposal. Rotation of the feed system to change the frequency of observation is now possible fairly routinely, and requires about 2 hours time for rotation and for set-up at the new frequency of operation, including antenna pointing.

Section 2.1.6 gives the measured system parameters of the GMRT antennas and some useful numbers for estimating the required observation time. Additional information can be found at

http://www.ncra.tifr.res.in/ncra/gmrt/gtac .

4.2.1.1 Interferometric Observations: Pre-observation Checklist

- contacted the observing assistant (the Operator) who would assist and run your observations.
- identified/selected a suitable bandpass calibrator
- flux density calibrator
- phase calibrator
- checked that all sources are visible during observing time
- prepared a source file in the right format
- prepared a command file using
  http://gmrt.ncra.tifr.res.in/gmrt_hpage/Users/Help/sys/setup.html
  and that this has been checked by the GMRT operator.
- calculated how much data the observations will generate, and obtained enough disk space to accommodate this. (Operator's too warn you of this!)

4.2.1.2 Observatory Supported Modes Below in the Table 3, we list the default settings for a continuum observations at a given frequency, and system parameters, including usable frequency recommended/available, respectively.

4.2.2 Pulsar

The GSB beamformer/pulsar receiver allows incoherent array (IA) and phased array (PA) mode observations using all the 30 antennas, with a maximum bandwidth of 32 MHz.

i For the IA mode observations, the actual number of antennas that can be added depends on the quality of the signals from the antennas, including effects of receiver instabilities and RFI. These effects vary with time, the radio band being used and depends on the choice of antennas. i.e. from central square antennas to arm antennas. Due to the current limitations of the data acquisition system, since observing cycle-20, the fastest sampling achievable in the IA mode is 30 μsec and 61 μsec for the 256

RF (MHz)	LO 1 (MHz)	IF-BW (MHz)	tpa					
150	218	16	156	156	218	218	62	62
235	304	16	242	242	304	304	62	62
325	255	32	306	306	255	255	51	51
610	540	32	591	591	540	540	51	51
1060	990	32	1041	1041	990	990	51	51
1170	1100	32	1151	1151	1100	1100	51	51
1280	1210	32	1261	1261	1210	1210	51	51
1390	1320	32	1371	1371	1320	1320	51	51
DUAL	680/304	32/16	629	253	680	304	51	51

Table 3: Supported defaults for a typical continuum observation.

channels and 512 channels, for both, 16 or 32 MHz modes of the GSB.

ii For the PA mode of observations, there is an algorithm that can phase any selected number of available, working antennas using interferometric observations of a point source calibrator. The phasing for central (~ 14) antennas works well for time scales ranging from one hour to a few hours, depending on the operational frequency and the ionospheric conditions. For the arm antennas or for the longer baselines, de-phasing can be more rapid.

iii Polarimetric pulsar observations are possible with the GSB, but instrumental polarisation effects for the GMRT are not fully characterised and observers will therefore need to carry out their own calibration.

iv For total intensity, the fastest sampling rate currently supported is 30 μsec and 61 μsec for the 256 channels and the 512 channels, respectively, for both, 16 and 32 MHz modes of the GSB.

v For the polar mode, the fastest sampling times are slower by a factor of 4 than these numbers, i.e., 122 μsec and 245 μsec for the 256 channels and the 512 channels, respectively for the corresponding GSB modes. Here, both IA and PA modes are available with a time tagging facility that is accurate to $\sim$240 $\times$ 10^{-9} sec with respect to the GPS-clock and the timing observations can be carried out.

The format of the beamformer data from the GSB is identical to that provided by the older hardware pulsar back-end. The final multi-channel data from the IA beamformer output can be recorded either on disk or on tapes (SDLT or LTO). The PA data from the GSB can also be recorded on disk or tapes (SDLT or LTO). User can choose either the total intensity signal or the four polarisations signal to record.

Additionally, the PA mode of the GSB also includes capability for recording the full time resolution voltage beam data with a facility for off-line coherent dedispersion. Finally, the GSB also allows a mode where the single IA and PA beams can be replaced by two IA beams or two PA beams, with independent antenna selections for each. This facilitates simultaneous dual-frequency observations of pulsars using the subarray mode (see Section 2.4) of the GMRT. Note that such observations involve special scheduling considerations, due to feed rotations and related overheads.

A Pulsar observing manual, for more details, is available at

http://gmrt.ncra.tifr.res.in/gmrt_hpage/Users/Pulsar/PULSAR_MANUAL.pdf .

4.2.2.1 Pulsar Observations: Pre-observation Checklist

- contacted the observing assistant (the Operator) who would assist and run your observations.
- calibrator for gain equalisation @300 count (close to target, ph-cal will work, but $>$ 5 Jy)
- perform phasing on the phase calibrator
- go to target pulsar
- configure IA+PA GAC

- start IA and/or PA ACQ (acquisition) + Process chain
- start data recording to the disk

4.2.3 Data Access

The data from the GMRT can be converted to FITS files using locally developed software, and analysed in standard packages like `AIPS` (see Section 4.4). These can be backed up on DVDs or external hard disks, written by Linux machines. Users are requested to bring their own media for backing up the data. Facilities for analysing GMRT data are available both at the Observatory and at the NCRA, Pune. Users requiring extensive computing facilities or large amounts of disk space for data storage or analysis should make their requirements known well in advance.

The online archive contains all GMRT data since 2002 (Cycle-01), and will also serve the user community with GMRT data. The entire archive is now on disk, and is available via the Archive Access Tool at

`https://naps.ncra.tifr.res.in/goa/mt/search/basicSearch` .

Data from all standard observations with the GMRT will be made public 18 months after the date of observation, and the TOO observations will be made public three months after the date of observation.

4.2.3.1 GMRT Data Archive Since GMRT observing cycle-1 (year 2002) observations, the entire archive is available via the web. The following url allows to view the data,

`https://naps.ncra.tifr.res.in/goa/mt/search/basicSearch` .

Presently this archive provide FITS (u, v) format files and native LTA format files. Data-base searches may be made based on a large number of user-specified criteria and one can download data via ftp protocols. Similar to all other observatories, GMRT data too are restricted to proprietary use by the proposing team for a period of 18 months from the date of the last observation in a proposal.

4.3 GMRT User Tool

A GMRT User Tool (GUT) has been released for users. It is a graphical interface to several existing GMRT software that are regularly used before observations (e.g. command file maker, rise and set time calculator), during observations (e.g. ondisp for monitoring the antenna status etc) and after observations (e.g. `tax`, `gvfits`) and includes a few other useful utilities. This can be accessed by saying `gut` at the UNIX prompt on any computer at the observatory.

4.4 Converting the Native LTA Format to FITS Format

Assuming that telescope operators gave you your data in the the native LTA format, 01TST01_OBJ.lta file – this file is in the raw telescope format, where lta stands for long term accumulation: programs available at the observatory, e.g., XTRACT, TAX, etc. used for quick check of the data quality operate on the LTA format. First run the program `listscan` to create "01TST01_OBJ.log" file. Edit the "log" file to select normalisation type, a subset of the data, provide your favourite name (UVDATA.FITS) to the output file, etc. Finally run `gvfits` (it provides UV data in J2000 epoch) on the edited log file. For example,

```
bash> listscan /PATH/DATE/01TST01_OBJ.lta
bash> vi 01TST01_OBJ.log
bash> gvfits 01TST01_OBJ.log
```

Note that these programs, e.g., listscan, gvfits, etc. are observatory based programmes, which are available on all GTAC computing machines at GMRT and NCRA.

5 Analysing Data from the GMRT: Straw Man Recipe

Although one can use FLAGCAL to flag and calibrate GMRT data (see Section 6.2.1 for more details) and move straight to Section 5.8 and perform imaging, here, we present a quick recipe for the analysis of GMRT data from scratch using classic AIPS. The users program source is named PROG-SRC. The interferometer phase is calibrated by observations of PH-CAL. The flux density scale and the bandpass is calibrated by observing AMPBP-CAL. The data-file containing this observation is named as UVDATA.FITS containing 256 spectral channels at 610 MHz.

5.1 Setting-up NRAO AIPS

Classic AIPS is installed on all machines at the observatory. Or, alternatively install AIPS on your machine from

http://www.aips.nrao.edu/index.shtml .

Next, for bourne shell,

```
bash> export FITS=/data/aips/FITS/
bash> source /data/aips/LOGIN.SH
```

or alternatively for csh/tsch shell

```
csh> setenv FITS /data/aips/FITS/
csh> source /data/aips/LOGIN.CSH
```

and start AIPS via

```
bash> /data/aips/START_AIPS
```

Typically at the AIPS prompt
> TASK 'taskname'
> INP to review the input parameters, called ADVERBS of 'taskname'
> GO runs the task 'taskname'
> EXPLAIN 'taskname' prints helpful information on the terminal or on the line printer
> UCAT lists cataloged UV files
> MCAT lists cataloged map files
> GETNAME n assigns the INNAME, INCLASS, INSEQ and INTYPE values
corresponding to file with catalog no. 'n'
> ZAP delete a catalog entry and its extensions files
> RESTORE 0 initializes AIPS and restores defaults
> KLEENEX exit from AIPS wiping the slate kleen

5.2 Loading Data

```
TASK 'FITLD'; DATAIN 'FITS:UVDATA.FITS'; GO
```

Say, this makes the catalog no. 1.

5.3 Indexing

```
TASK 'INDXR'; GETN 1; CPARM(3) = 1; GO
```

This creates NX and CL (ver. 1) tables.

5.3.1 HEADER Information

.

```
GETN n; IMHE
```

It lists header information from the catalog file no. 'n' selected. It also lists tables that have two letter names, which are

- HI Human readable history of things done to your data. Use AIPS task PRTHI to read it and task PRTAB to read other tables.
- AN Antenna location (and polarisation) tables.
- NX Index into visibility file based source name and observation time.
- SU Source table contains the list of sources observed and indexes into the frequency table. The flux densities of the calibration sources are entered into this table.
- FQ Frequencies of observation and bandwidth with index into visibility data.
- CL Calibration (ver. 1) table describing the antenna based gains. The goal of calibration is to create a good CL ver. 2.

5.4 Data Editing / FLAGging / Viewing

```
TASK 'QUACK'; OPCODE 'BEG'; APARM 0.5; GO
```

This FLAGs the bad points at the beginning of each scan and creates a Flag Table (FG).
Again

```
TASK 'UVFLG'; ANTEN ?,0; TIMER ?; OUTFGVER=1; INP; GO
```

FLAGs bad UV data!

```
TASK 'LISTR'; OPTYP 'SCAN'; DOCRT 1; SOURC ' '; INP; GO
```

This LISTR task lists your UV data in a variety of ways and the above inputs show the summary of the sources in the input data file.

5.5 Gain Calibration

5.5.1 SETJY

Enter the absolute flux density of the primary calibrator in the SU table,

```
TASK 'SETJY'; SOURCES 'AMPBP-CAL', ' '; OPTYPE 'CALC'; GO
```

5.5.2 CALIB

Solve for the antenna based amplitudes and phases for AMPBP-CAL and PH-CAL,

```
TASK 'CALIB'; CALSOUR 'AMPBP-CAL', 'PH-CAL, ' '; BCHAN Y; ECHAN Y;
REFANT X; SOLINT 2; GO
```

Here channel 'Y' is a RFI-free channel from the dataset and antenna 'X' is assumed to be 'good'. This will generate the solution SN table with ver. 1. The calibrated data can now be plotted using the AIPS task UVPLT.

5.5.3 GETJY

Bootstrapping the flux density to the phase calibrator

```
TASK 'GETJY'; SOURCES 'PH-CAL', ' '; CALSOUR 'AMPBP-CAL', ' '; SNVER 0; GO
```

These values too are now written in the SU table.

5.5.4 CLCAL

Interpolate the gains
```
TASK 'CLCAL'; SOURCES 'AMPBP-CAL'; CALSOUR 'AMPBP-CAL', ' ';
OPCODE 'CALI'; SNVER 0; INVER 0; GAINVER 1; GAINUSE 2; REFANT X; GO
```
Now the gains have been interpolated for the time instances of the program source. The solution (SN / CL) tables can be plotted using the AIPS task SNPLT.

5.5.5 Bandpass Calibration

```
TASK 'BPASS'; CALSOUR 'AMPBP-CAL', ' '; DOCAL 1; DOBAND −1; SOLINT 0;
REFANT X; BPASSPRM(5) 1; ICHANSEL Y Y 1 0; GO
```
The bandpass solutions (BP table) can be plotted using the AIPS task POSSM.
```
TASK 'POSSM'; APARM(8) = 2; NPLOTS = 6; GO.
```
Again, ICHANSEL 'Y' is a RFI-free channel, which was used as a reference channel for calibration and antenna 'X' is assumed to be 'good'. Now CL table ver. 2 with the UVDATA file can be deleted using
```
INP EXTDEST; INEXT 'CL'; INVERS 2; EXTDEST.
```

5.5.6 CLCAL

Interpolate the gains
```
TASK 'CLCAL'; SOURCES ' '; CALSOUR 'AMPBP-CAL', 'PH-CAL', ' ';
OPCODE 'CALI'; SNVER 0; INVER 0; GAINVER 1; GAINUSE 2; REFANT X; GO
```
Now the gains have been interpolated for the time instances of the program source. The solution (SN / CL) tables can be plotted using the AIPS task SNPLT.

5.6 Saving your Tables

```
TASK 'TASAV'; OUTNA = INNA; OUTDI = INDI; INP; GO
```

5.7 Splitting the Target Source

```
TASK 'SPLAT' SOURCES 'PROG-SRC', ' '; DOCAL 1; GAINUSE 2; DOBAND 3;
BPVER 1; FLAGVER 1; GO
```
This would make a new UVDATA file, PROG-SRC.SPLAT.1 containing the calibrated data for the program source that is free from bad data. Alternative one could also use AIPS task SPLIT.

5.8 Imaging: Continuum

Here I am assuming the imaging is being performed at 610 MHz and we would perform the wide field imaging.
```
TASK 'IMAGR'; SOURCES 'PROG-SRC', ' '; BCHAN 10; ECHAN 246; NCHAV 237;
CELLSIZE 0.8 0.8; IMSIZE 1024 1024;
RASHIFT = -750, 0, 750, -750, 0, 750, -750, 0, 750, 0;
DECSHIF = 750, 750, 750, 0, 0, 0, -750, -750, -750, 0;
DO3DIMAG 1; OVERLAP 2;
NITER 1000000; DOTV 1; GO
```
Here, we are doing (wide field) imaging in the so called manual- / interactive-mode. We would stop the task once we have performed the complete deconvolution, CLEAN process. Also, this would make nine BEAMs and nine CLEAN fields as the image catalog files. These are shifted from the phase-centre using RASHIFT

and DECSHIF defined above. One can stitch these nine CLEAN fields using
```
TASK 'FLATN'; GETN m; NFIELD 9; NMAPS 1; IMSIZE 3000 3000; GO
```
where 'm' is the first image-file comprising nine CLEAN fields.

Note that, instead one could use a SETFC to make a BOXFILE for input to IMAGR.

In order to present your imaging results, use TASK 'KNTR', TASK IMEAN, TASK IMSTAT, etc.

5.9 Imaging: Spectral-line

Here I am again assuming the spectral imaging is being performed at 610 MHz and the wide field imaging is necessary. Also, I am assuming that first 20 channels are free from spectral-line information and rest of the channels (from 21 to 256) have spectral-line information.

5.9.1 Continuum Image

Making a continuum image of the line-free channels,
```
TASK 'IMAGR'; SOURCES 'PROG-SRC', ' '; BCHAN 8; ECHAN 17; NCHAV 10;
CELLSIZE 0.8 0.8; IMSIZE 1024 1024;
RASHIFT = -750, 0, 750, -750, 0, 750, -750, 0, 750, 0;
DECSHIF = 750, 750, 750, 0, 0, 0, -750, -750, -750, 0;
DO3DIMAG 1; OVERLAP 2;
UVTAPER 60 60; UVRANGE 0 90;
NITER 1000000; DOTV 1; GO
```

5.9.2 Subtracting the Continuum

Now subtracting the continuum emission from all channels,
```
TASK 'UVSUB' GETN n; GET2N m; NMAPS 9; GO
```
where 'n' and 'm' are catalog no. for PROG-SRC.SPLAT.1 and PROG-SRC.ICL001.1, respectively to generate PROG-SRC.UVSUB.1. Alternatively, AIPS tasks UVLIN / IMLIN could also be used to subtract continuum. Note that 'm' is the first image-file comprising nine CLEAN fields.

5.9.3 Making a Spectral Cube

Imaging the continuum-subtracted data set
```
TASK 'IMAGR'; BCHAN 21; ECHAN 246; CELLSIZE 0.8 0.8; IMSIZE 1024 1024;
UVTAPER 60 60; UVRANGE 0 90; NITER 0; DOTV 1; GO
```
This would provide the image cube.

5.9.4 Extracting the Spectrum

Finally extracting the spectrum,
```
TASK 'ISPEC'; GO
```
gives the spectrum averaged over a chosen area (perform this with an appropriate choice of ADVERBS) of the image.

Apart from presenting your imaging results discussed above (Section 5.8), in order to present your spectral line results, use TASK 'MOMNT', TASK IMEAN, TASK IMSTAT, etc.

6 Miscellaneous

6.1 Making the Observations: Logistics

6.1.1 Accommodation, Travel & Help for Visitors to the GMRT / NCRA

The telescope is located near Khodad village, which is about 80 km north of Pune. The telescope site houses laboratories, complementing facilities like guest house, canteen, library, etc. The observatory can be reached using the daily shuttle service starting from NCRA, Pune at 0700 Hrs in the morning, or by direct taxi from Mumbai or Pune. The closest town, Narayangaon, is about 14 km from the observatory and is connected to Pune and Mumbai by public bus transport system. If information is given in advance, transportation arrangements can be made for the observers from the Narayangaon bus stand to the observatory. See

http://www.ncra.tifr.res.in/ncra/gmrt/gtac

for more details on various general aspects about observing at the GMRT, including a road-map for travel to the observatory. Several general and administrative guidelines for visitors to help them organise are available at administrative-info general-info including handy information, available at handy-info and road map information, available at raod-map .

6.1.1.1 Absentee Observing All users are expected to be present for observations. However, in case of short observations of routine nature users can request remote observing by writing to the
"GMRT - Operations", at

gmrtoperations AT ncra DOT tifr DOT res DOT in

with a copy to

Y. Gupta ygupta AT ncra DOT tifr DOT res DOT in .

6.2 Tools

Various tools have been developed to visualise the data in quasi real-time. Some of the most used tools are mon displays real time snapshots of cross-correlations, self-correlations, antenna bandshape, phase and amplitude etc.; tax gives offline plots of cross-correlations, self-correlations, antenna bandshape, phase and amplitude etc.; gdp gives information on non-working antennas, bad baselines, phase jumps, delay jumps etc. These tools are available for all users and can be run with some help from on duty telescope operators. Additionally, several useful online scripts available are,
GMRT online archive access: A portal to find data from the GMRT archive

https://naps.ncra.tifr.res.in/goa/mt/search/basicSearch

GMRT observing command file creator: Create your observing command files

http://gmrt.ncra.tifr.res.in/gmrt_hpage/Users/Help/sys/setup.html

GMRT frequency calculation: Calculate your 'TPA' values

http://gmrt.ncra.tifr.res.in/gmrt_hpage/Users/Help/sys/freq.html

GMRT source rise, transit and set times: Rise, transit and set times for the source(s) at GMRT

http://gmrt.ncra.tifr.res.in/gmrt_hpage/Users/Help/sys/time.php ,

which can be used for optimising the observing strategy.

6.2.1 A Flagging and Calibration Pipeline

FLAGCAL is a flagging and calibration program meant for use with GMRT data. The input to FLAGCAL is a raw GMRT FITS file, and its output is a calibrated and flagged FITS file, which can be directly used for imaging and further processing. This can be accessed by saying flagcal at the UNIX prompt on any computer at the observatory. FLAGCAL is flexible and highly configurable; information and help on using

it is available in the NCRA library dspace technical report collection, viz,
http://ncralib1.ncra.tifr.res.in:8080/jspui/handle/2301/581.

6.3 Publication Guidelines

A copy of the final paper/preprint should be mailed to the "Secretary - Operations", at
secr-ops AT ncra DOT tifr DOT res DOT in
and
library AT ncra DOT tifr DOT res DOT in
or sent to the following address:
Secretary - Operations,
National Centre for radio Astrophysics (NCRA–TIFR),
Post Box 3, Ganeshkhind P.O.,
Pune University Campus,
Pune 411007, INDIA.

6.3.1 Acknowledging the GMRT

All publications resulting from GMRT data should have an acknowledgment of the form: "We thank the staff of the GMRT that made these observations possible. GMRT is run by the National Centre for Radio Astrophysics of the Tata Institute of Fundamental Research."

6.3.2 Dissertations

We request students whose dissertations include observations made with GMRT to provide copies of their theses to
secr-ops AT ncra DOT tifr DOT res DOT in
or sent to the following address:
Secretary-Operations,
National Centre for radio Astrophysics (NCRA–TIFR),
Post Box 3, Ganeshkhind P.O.,
Pune University Campus,
Pune 411007, INDIA
for inclusion and maintenance at the NCRA-GMRT library.

6.4 Key Personnel

Note: queries should be made directly to the "Secretary - Operations", at
secr-ops AT ncra DOT tifr DOT res DOT in .
However, you may e-mail any of the following:
C.H. Ishwara Chandra ishwar AT ncra DOT tifr DOT res DOT in
N.G. Kantharia ngk AT ncra DOT tifr DOT res DOT in
Y. Gupta ygupta AT ncra DOT tifr DOT res DOT in
with copies to
"Secretary - Operations" secr-ops AT ncra DOT tifr DOT res DOT in
and
"GMRT - Operations" gmrtoperations AT ncra DOT tifr DOT res DOT in .

6.5 Documentation

GMRT primary beam shapes
http://www.ncra.tifr.res.in:8081/~ngk/primarybeam/beam.html
and
http://www.ncra.tifr.res.in:8081/~ngk/primarybeam/report_lband_beam.ps .
Technical report on finding the beamshape parameters
http://www.ncra.tifr.res.in:8081/~ngk/primarybeam/report_lband_beam.ps .
A real-time software backend for the GMRT (Roy et al., 2009)
http://arxiv.org/abs/0910.1517 .
FLAGCAL: A flagging and calibration pipeline for GMRT data
http://ncralib1.ncra.tifr.res.in:8081/jspui/handle/2301/581 .
NCRA annual report (2010−2011)
http://www.ncra.tifr.res.in/library/annual/report-10-11.pdf .

6.6 Modification History

This user's manual is based on the previous versions, i.e., the document involves inputs from several people, particularly those associated with the GMRT. We express our thanks to everyone of them.

ver. 3 :	This version[†]
ver. 2.2 :	M. S. Jangam, N. G. Kantharia & S. S. Sherkar
ver. 2.1 :	M. S. Jangam & D. J. Saikia
ver. 2 :	D. V. Lal, A. P. Rao, M. S. Jangam & N. G. Kantharia
ver. 1 :	Judith Irwin

[†]Compared to previous versions, this draft includes updated specification of the GMRT, straw man's GMRT data analysis recipe and lists ongoing GMRT upgrades.

6.6.1 Acknowledgments

Format and style are also based on manuals from other observatories, e.g., "ATCA Users Guide", "VLA Observational Status Summary", etc. for uniformity. In case of questions on the material, or suggestions that would enhance the clarity of this guide, please contact
D. V. Lal dharam AT ncra DOT tifr DOT res DOT in .

7 Ongoing Developments

7.1 GMRT Upgrades

A major upgrade of the GMRT is currently underway. The main goals of this upgrade are to provide (i) as far as possible, seamless frequency coverage from 50 MHz to 1500 MHz, (ii) improved sensitivity with better quality receivers, (iii) a maximum instantaneous usable bandwidth of 400 MHz, (iv) a revamped and modern servo system, (v) a new generation monitor and control system, (vi) improvements in the antenna mechanical structure, and (vii) matching improvements in infrastructure and computational facilities. The upgrade will result in significant changes to almost all aspects of the GMRT receiver chain and other systems. However, full care is being taken in the design of the new systems to ensure that the performance of the existing GMRT is not affected as the upgrade is implemented.

Below, we present salient features of the upgrades of individual systems. Many of these upgrade activities are now past the prototype development and testing stages, and are entering mass production and

commissioning stages. These latter phases are expected to go on for the next 1–2 year or so.

7.1.1 Servo System

[Team members: S. Sabhapathy, S.K. Bagade, A. Kumar, S.M. Burle, A. Bhumkar, S.J. Bachal, B. Thiyagarajan, D.D. Ghorpade, T.S. Haokip, A. Poonattu, D.D. Temgire]

As part of the upgrade of GMRT servo system, extensive tests for validation of new Brush-less DC motors and drives were carried out on C04 antenna. The new system was integrated with the existing station servo control and was commissioned in a Radio Frequency Interference free enclosure in March 2011. The system performance was compared with the brushed motor systems in other antennas and was found to be similar. The system is performing satisfactorily since its commissioning. The mass production of this system for three more antennas has begun and procurement for six more antennas is in progress. A new interface was designed and validated for PC/104 based digital position loop and tests on C02 antennas are continuing. The interlock system on all antenna except C12 has now been upgraded to solid-state interlock system. Likewise, feed position system is also in the process to be upgraded on more antennas.

7.1.2 RF Front-end Systems

[Team Members: S. Kumar, A. Raut, V.B. Bhalerao, S. Ramesh, M. Parathe, Ankur]

In feeds and front-end electronics, the existing 325 MHz feed will be replaced with a broadband feed operating from 250 to 500 MHz, along with a broadband low noise amplifier with improved noise temperature. A new feed operating from 550 to 900 MHz will replace the existing 610/235 MHz co-axial feed, also with a matching LNA with an improved noise figure. The 150 MHz feed will also get replaced with a wider bandwidth feed. As far as possible, it is being ensured that the new feeds will cover the frequency range provided by the existing narrow band feeds that they are replacing, with similar or better level of sensitivity.

The final upgraded L-Band (1000-1500 MHz) receiver for the GMRT has been installed on 22 antennas of the GMRT. This improved receiver has high dynamic range amplifiers incorporated for better immunity against higher levels of radio frequency interference (RFI). Rest of the feed design has not been modified. In addition, band-reject filters have been placed to suppress the RFI from GSM 900 and CDMA cellular mobile RF carriers

7.1.3 Low Noise Amplifier

[Team Members A.P. Kumar, B. Hanumanthrao, A.N. Raut, G. Sankarasubramanian]

A final prototype of the 550-900 MHz Low Noise Amplifier has been designed and successfully tested on the GMRT antennas. In order to provide a wideband feed for the GMRT to cover low frequencies, a dipole feed with a conical reflector has been designed, fabricated and successfully tested on the GMRT antenna. This feed gives uniform sensitivity for the frequency range of 280-520 MHz.

7.1.4 Fiber-Optics

[Team members: S. Sureshkumar, P. Raybole, S. Lokhande, M. Gopinathan]

The optical fibre link to each antenna will be modified to provide additional wavelengths to bring back the broadband RF signals directly to the receiver room, without disturbing the existing narrow bandwidth path that brings back the two IF signals.

As part of the GMRT upgrade, Wavelength Division Multiplexing based RF Fiber-Optic links have been designed, fabricated and installed on six GMRT antennas. The system uses four wavelength channels operating at the 1550 nm window. Two channels are used to bring the full RF band (10-1500 MHz) for the two orthogonally polarised signals directly from the Front-End system without any frequency translation, to

the central station for further signal processing. A third channel is used to support the existing GMRT return link from the antenna, thereby allowing for coexistence of the old and new systems

1 Gigabit Ethernet links from the central station to the GMRT antennas have been installed on 4 antennas of the GMRT, for control and monitor applications.

As a part of the RFI mitigation and modernisation efforts at the GMRT, a Fiber-Optic LAN has been implemented at the GMRT Observatory building. This network has 144 user locations, connecting all the laboratories and offices in the building

7.1.5 Back-end Systems

[Team members: B. Ajit Kumar, S. Gupta, N.D. Shinde, D.K. Nanaware, A. Ganla, S.V. Phakatkar, P.J. Hande, A. Vishwakarma, S.C. Chaudhari, M.V. Muley, H. Reddy, I. Halagalli, K. Buch, G.J. Shelton, I.S. Bhonde, S.S. Kudale]

In the receiver room, a separate and parallel signal path will convert the broadband RF signals to base-band signals with a maximum bandwith of 400 MHz, which will be processed with a new digital back-end system (correlator `plus` beamformer `plus` pulsar receiver) that can handle the full 400 MHz bandwidth. This entire chain will run in parallel with the existing 32 MHz bandwidth receiver chain, without affecting its performance in any way. The team is using the CASPER (Centre for Astronomy Signal Processing and Research) based design approach for implementation of the digital back-ends. We also plan to add facilities for RFI cancellation (in both analog & digital domain) and raw data recording and software based back-ends.

Analog Back-end System: A versatile analog back-end has been developed to process the RF signal received from antennas using high dynamic range circuits. The circuit has been analysed and optimised for appropriate gain flatness and one set of final prototype has been wired and tested in the lab. The test results are as expected and the circuit is now ready for mass production. Synthesiser circuits for Frequency conversion before digitisation is also finalised. These circuits will allow different observing bands in different antennas. The phase noise of the circuit was tested and found to be -90 dBc/Hz @1 KHz offset, which is 30 dB better than the existing GMRT receiver.

Digital Back-end System: The digital back-end digitizes the data and implements the correlator and beamformer for the interferometry and array outputs, respectively. A four antenna FPGA based correlator was completed and the first light signals were obtained with this. It is now in final stages of test and release. The design has a modular approach, so it can be easily expanded to a 30 antenna design by adding additional processing boards. The system uses 8 Virtex-5 FPGA boards, 4 ADC boards, one 10 GbE switch and a control PC. The design incorporates coarse, fine delay and fringe corrections and has been tested using GMRT antennas. We have also developed a hybrid design using a CPU/GPU based approach. In this design, a FPGA board is used to send the digitized data to a PC in 10 GB packets. GPU boards hosted by the PC are used to process these data and provide correlated outputs. A two antenna, 200 MHz bandwidth, 8-bit correlator based on this concept has been implemented and tested.